POSSIBLE STELLAR METALLICITY ENHANCEMENTS FROM THE ACCRETION OF PLANETS

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Received ______________________; accepted ______________________

ABSTRACT

A number of recently discovered extrasolar planet candidates have surprisingly small orbits, which may indicate that considerable orbital migration takes place in protoplanetary systems. A natural consequence of orbital migration is for a series of planets to be accreted, destroyed, and then thoroughly mixed into the convective envelope of the central star. We study the ramifications of planet accretion for the final main sequence metallicity of the star. If maximum disk lifetimes are on the order of ~ 10 Myr, stars with masses near $1.0 M_{\odot}$ are predicted to have virtually no metallicity enhancement. On the other hand, early F and late A type stars with masses $M_{*} \approx 1.5$–$2.0\ M_{\odot}$ can experience significant metallicity enhancements due to their considerably smaller convection zones during the first 10 Myr of pre-main-sequence evolution. We show that the metallicities of an aggregate of unevolved F stars are consistent with an average star accreting ~ 2 Jupiter-mass planets from a protoplanetary disk having a 10 Myr dispersal time.

Subject headings: stars: abundances, stars: stellar statistics, stars: planetary systems

1. Introduction

The detection of planets orbiting nearby solar type stars (e.g., Mayor & Queloz 1995) was a much-anticipated discovery. The existence of massive planets at small orbital radii ($r \leq 0.1$ AU), however, came as a surprise. The first such system found – 51 Peg – has a planetary mass $M_P \sin i = 0.47\ M_{Jup}$ and a semi-major axis r=0.05 AU (Marcy & Butler 1996). Similar close companions have been detected around υ And ($M_P \sin i$=0.68 M_{Jup}, r=0.057 AU), 55 Cnc ($M_P \sin i$=0.84 M_{Jup}, r=0.11 AU), and τ Boo ($M_P \sin i$=3.87 M_{Jup}, r=0.0462 AU) (see Butler et. al 1997).

The existence of Jupiter-mass planets very close to their primary stars strongly suggests that orbital migration has occurred in these systems. The planets are posited to have formed at large radii (5–10 AU where most of the disk mass resides), and thereafter transported inward as a result of tidal interactions with with the protoplanetary disk. Successful models of orbital migration have been constructed (e.g., Lin, Bodenheimer, & Richardson 1996; Trilling et al. 1997) that demonstrate the plausibility of this hypothesis.

As a natural consequence of the migration scenario, a series of planetary-mass objects might be added to the star during its pre-main-sequence development (Gonzalez 1997ab; Lin 1997; Jeffery, Bailey, & Chambers 1997). Because the accreted planets are (presumably) metal rich, the metallicity of the parent star is enhanced. The degree of metallicity increase depends sensitively on the fraction of the star over which accreted planets are distributed. A planet added to a fully convective star is folded into the entire stellar mass and leads to a negligible metallicity enhancement. If the parent star is largely radiative, with only a small outer convective zone, metallicity enhancements can be much larger. If the convective envelope subtends 2% of the mass of a 1 $M_\odot$ star, and the star accretes a Jupiter-like planet, the metal enhancement $\Delta Z \sim 0.005$ is both significant and observable.

As a general trend, solar type stars begin their pre-main-sequence evolution on the

Hayashi track with a fully convective stellar configuration. After several million years, radiative cores appear and the size of the convective envelope steadily decreases over the next ten million years or so. Main sequence solar mass stars have relatively small outer convection zones which comprise only a few percent of the stellar mass. ZAMS stars with masses greater than $\sim 1.3\ M_\odot$ are radiative up to the surface. The expected lifetimes for protoplanetary disks lie in the range 1–10 million years, indicating that early F stars are likely to exhibit a metallicity trend resulting from the accretion of planets.

This letter is organized as follows. In §2, we outline the basic theoretical issues involved in determining stellar metallicity enhancements arising from the accretion of planets. We then use these considerations to examine a sample of nearby F stars in §3. We conclude in §4 by discussing our results and their implications.

2. Metallicity Enhancement through Accretion of Planets

The metallicity of the convective envelope of a young star will evolve as it accretes planets. In this section, we develop a simple model of this process. For the sake of definiteness, we assume that the accretion of Jupiter-type planets is determined by an accretion function $F(t)$ which specifies the mass in planets accreted per unit time. Planets, of course, are discrete objects, so the continuous function $F(t)$ applies to an ensemble average of systems rather than particular individual systems. The range of possibilities is adequately covered if we use a class of accretion functions having the general form

$$F(t) = F_0[1 - (t/t_D)]^n \,, \tag{1}$$

which defines a three parameter family. The constant F_0 sets the overall normalization; the time constant t_D is the total time interval over which planets are accreted; the index n is a shape parameter that specifies how planet accretion falls off over time. The total mass in

planets accreted over the entire time interval is given by

$$\Delta M = \frac{F_0 t_D}{n+1}\,, \tag{2}$$

and the mean number of accreted planets is $N_P = \Delta M / M_P$, where M_P is the mean mass of the planets. The time t_D is determined by the life time of the circumstellar disk. When the disk mass becomes too small, orbital migration can no longer operate and planets will no longer be accreted. Expected disk life times are 1–10 million years, with considerable variation and uncertainty (see, e.g., the review of Strom, Edwards, & Skrutskie 1993).

Notice that rocky debris will also be accreted at some level. The inward spiral of a gas-giant is likely to enforce the accretion of rocky material inside its orbit (assuming the evolution is roughly similar to that of our Solar System). However, our numerical experiment is limited to Jupiter-like planets.

The differential equation describing the metallicity Z of the convective envelope of a particular star as a function of time can be written as

$$\frac{dZ}{dt} = (Z_P - Z)\frac{F(t)}{M_C(M_*, Z, t)}, \tag{3}$$

where M_C is the mass of the convective envelope as a function of time. We assume that the stellar mass M_* does not change appreciably as planets are subsumed. We expect that the metallicity Z_P of the planets will be comparable to that of Jupiter, and hence $Z_P \approx 0.1$. We also implicitly assume that the distribution of heavy elements in the accreted planets is the same as the distribution of heavy elements in the Sun.

The three-dimensional function $M_C(M_*, Z, t)$ must be obtained from stellar evolutionary calculations. Using a grid of pre-main-sequence tracks (Forestini 1994) for model stars of mass $M_* = 1.0 - 2.5\ M_\odot$ at metallicities of $Z = 0.02$ and 0.04, we construct the following analytic expression for the mass of convective envelopes

$$M_C(M_*, z, t) = M_* (1 - x^2)^2 e^{-x^2}\,, \tag{4}$$

where we have defined

$$x \equiv \frac{t\, M_*^{3.1}}{40(1 + 15(Z - 0.02))}\,. \tag{5}$$

This smoothly varying function reproduces the calculated values of $M_C(M_*, Z, t)$ to the required accuracy. It provides accurate values for both the evolutionary time required to obtain a particular star's ZAMS convective envelope, and also the mass of that envelope.

The predicted effect of accreted planets on main sequence metallicities is illustrated in Figure 1, where several numerical solutions to eq. (3) are plotted. Our "reference case" uses representative values $t_D = 10$ Myr, $\Delta M = 2 M_{Jup}$, and shape parameter n=2. When planets are accreted onto a fully radiative star, the planet's mass M_P (taken to be 1 $M_{Jup} = 0.001$ $M_\odot$) is assumed to mix with an additional mass $4 M_P$ of the parent star's envelope. Figure 1 indicates that the disk lifetime t_D is the most sensitive parameter. In particular, if the time scale for disk dispersal is $\sim$ 1 Myr, then no metallicity trend from planetary accretion should be discernible in a sample of stars in the mass range $M_* = 1.0 – 2.5$ $M_\odot$.

3. A Search For a Metallicity Trend in the Nearby F Stars

To examine the plausibility of the planetary accretion scenario, we have used a catalog of nearby F stars (Marsakov & Shevelev 1995; hereafter MS) to search for trends in metallicity. The MS catalog is based on the compilation of Hauck & Mermilliod (1985), and contains 5489 F stars within 80 pc of the Sun. The MS data set lists coordinates and kinematical properties for each star, along with metallicities (as [Fe/H]), effective temperatures, absolute magnitudes, ages [1], and other data. MS determine [Fe/H] from *uvby* photometric measurements using the calibration of Carlberg et. al (1985). We have found that this calibration introduces a slight (positive) correlation between metallicity Z and temperature $T_{\rm eff}$. We use

[1]The ages are based on pre-HIPPARCOS parallaxes.

an alternate calibration (Schuster & Nissen 1989), which does not exhibit such a correlation, as determined by comparing the [Fe/H] values with measurements obtained via high resolution spectroscopy (Rocha-Pinto & Maciel 1996, Wyse & Gilmore 1995). In re-computing the metallicities for each star in the MS catalog, we use *uvby* photometry taken directly from the Hauck & Mermilliod (1985) compilation. The uncertainty in this method of determining metallicity for each star is 0.16 dex (Schuster & Nissen 1989).

MS state that their data set is "practically full" in the 80 pc limiting volume for stars having corrected colors $b-y < 0.32$ (2017 stars), and 60% full over the entire F2–G2 spectral interval (5800 K $< T_{\rm eff} <$ 7000 K). Because the locus of stars having $b - y = 0.32$ does not correspond to a perfectly vertical line in a Z vs $T_{\rm eff}$ diagram, we seek to avoid complications introduced by incompleteness by accepting only catalog stars lying within a distance $d = 40$ pc. We also reject from consideration all stars belonging to unresolved binaries.

Accreted planets generate a trend in the metallicity of stars as a function of mass, rather than effective temperature. We must thus determine the stellar mass as a function of metallicity and temperature, i.e., $M_*(Z, T_{\rm eff})$. For a given effective temperature and metallicity, we make bilinear interpolations from the ZAMS models (Forestini 1994) to obtain the stellar mass. The MS data set is binned according to effective temperature (all the F stars), rather than mass. The lower end of the $T_{\rm eff}$ range (5800–7000 K) probes down to metal poor solar mass stars, whereas the high end of the $T_{\rm eff}$ range includes metal rich stars with masses up to $\sim 1.8\ M_\odot$. However, only a small range in mass ($1.42 - 1.52\ M_\odot$) is represented over the entire range of metallicities in the sample.

In order to search the MS stars for a specific metallicity enrichment trend, as predicted by eq. (3), we perform Monte-Carlo simulations which add individual planets to an ensemble of stars in accordance with particular choices for the accretion function. The metallicity trend in the simulated stellar distribution can then be compared with the trend present in the MS

catalog stars.

We selected 1000 stars in the mass range 1.0 $M_\odot < M_* < 2.5$ $M_\odot$ by sampling the initial mass function (Salpeter 1955). These stars were then assigned metallicities in accordance with the metallicity distribution for G dwarfs in the Solar neighborhood having [Fe/H] ≥ -0.4 (Rocha-Pinto & Maciel 1996). The metallicities in their observed distribution were obtained from *uvby* photometry and the Schuster & Nissen (1989) calibration, just as we have done. Because G star progenitors are largely convective during the ~ 10 Myr disk dispersal time, they should not exhibit an overall metallicity trend from the accretion of Jupiter-type planets. Indeed, the analysis of Rocha-Pinto & Maciel (1996) reveals no significant trend.

The 1000 stars were allowed to accrete planets in accordance with the distribution given by eq. (1). The masses of individual accreted planets were allowed to vary about the mean value of 1 M_{Jup} by sampling from a gaussian distribution with variance $M_{Jup}/3$. The number of planets ingested by each star was sampled from a gaussian distribution with variance 1/3 centered on $N_P = 2$ (rounding the sample to the nearest integer). The times at which planets were accreted were sampled directly from eq. (1), with $n = 2$, and $t_D = 10$ Myr. The accreted planets (with $Z_P = 0.1$) were assumed to mix thoroughly with the convective stellar envelope, enhancing its metallicity. In the first simulation, planets entering fully radiative stars were assumed to mix with 4 M_{Jup} (0.004 $M_\odot$) of the sub-photospheric stellar material (this value is consistent with numerical estimates of G. Bryden, private communication 1997).

The distribution of metallicity enhanced stars is shown in Figure 2. After planetary accretion takes place, only 291 stars fall in the domain shown, i.e., 6000 K $< T_{\rm eff} <$ 7000 K and $0.01 < Z < 0.06$. The arrows connect the (Z,$T_{\rm eff}$) value that each star would have with no planet accretion with the (Z,$T_{\rm eff}$) value obtained after including planet accretion. The figure also shows the zero-age F stars in the MS catalog that have distances $d < 40$ pc and fall within the plot limits (305 stars). We have used only unevolved stars (MS catalog stars

whose ages are consistent with a ZAMS identification) in order to minimize the complications brought on by both main sequence stellar evolution and the overall metallicity evolution of the Milky Way.

A linear fit to the original metallicities of the 291 simulation stars shows a slight positive slope of $0.6 \pm 0.8 \times 10^{-6}\mathrm{K}^{-1}$. A linear fit to the distribution of enhanced metallicities shows a larger slope of $2.5 \times 10^{-6}\mathrm{K}^{-1}$, which is consistent and comparable with the slope of $1.8 \pm 1.7 \times 10^{-6}\mathrm{K}^{-1}$ obtained from the 305 MS catalog stars.

In Figure 3, we show the results of a simulation which contains the same parameters as the simulation described above, except that we have changed the minimum mixing mass to 2 M_{Jup}. Notice that this simulation predicts too many high metallicity stars compared to the MS data set. We can thus conclude that accreted planets must mix with more than 2 M_{Jup} of stellar material, or that less than 2 planets per star can be accreted.

4. Discussion

We have studied the possible enhancement of stellar metallicity due to the accretion of planets. In particular, we have developed a simple theoretical model to incorporate metal enhancements due to accreted planets. We have then searched for trends in metallicity within a well defined sample of nearby F stars. Our results are summarized below.

[1] The effects of planet accretion on stellar metallicity are strongly dependent upon the total stellar mass. Stars with masses comparable to the Sun have large convective envelopes for nearly the entire time interval over which planets are expected to be accreted. These stars will show essentially no metal enhancements. Higher mass stars, with $M_* \sim 1.5 M_\odot$, have much smaller convective envelopes during their pre-main-sequence phases and can suffer relatively larger metal enhancements. We have found that the disk lifetime is the most

important parameter in determining the metallicity trend. Disk lifetimes $t_D > 10$ Myr can lead to significant metallicity increases for F stars which accrete planets.

[2] The MS catalog of nearby F stars shows only marginal evidence for a trend of increasing metallicity with increasing stellar mass. Such a trend is consistent with the metallicity increases expected from the accretion of about 2 Jupiter-mass planets per star over a disk dispersal lifetime of 10 Myr. This work can only point out the *possible* existence of this trend. A more refined analysis using a larger sample of stars and/or more accurate metallicity determinations is required to definitely establish or rule out its existence.

Indeed, a great deal of follow-up work can be done to elucidate these concepts further. Because the predicted metallicity trends resulting from planetary accretion are fairly subtle, a larger and more complete sample of stars, with an increased mass range, is needed to obtain the statistics necessary for a firm conclusion. The trend is predicted to be most significant for stars in the mass range 1.5 – 2.5 $M_{\odot}$. It is also highly advantageous to obtain the stellar metallicities from spectroscopy, rather than the cruder measure afforded by *uvby* photometry. [2] It is possible that an unforeseen effect is influencing the $b - y$ index as the spectral type changes. However, one additional complication is that metal lines are more difficult to observe for A stars. Another possible improvement is to recalibrate the Schuster & Nissen equation with recent spectroscopic metallicity estimates.

Notice that this approach – searching for metallicity trends in a wide sample of nearby stars – is complementary to directly studying the specific systems which are thought to have planets. The stars in these newly discovered planetary systems seem to be systematically

[2] We note that the spectroscopic metallicity estimates of Edvardsson et al. (1993) are smaller than the photometric metallicity estimates for the most metal-rich stars (see also Wyse & Gilmore 1995).

high in metallicity (e.g., Gonzalez 1997ab). For small numbers of systems, however, it is difficult to separate the effects of metallicity enhancement from high initial metallicity. We note, for example, that planetary accretion does not account for the high metallicities of 55 Cnc and 51 Peg; these G stars should have large convection zones throughout the planet accretion phase of evolution. To circumvent the initial metallicity ambiguity, one can search for metallicity trends among F and G dwarfs in open clusters and binary systems. Wide binaries containing both an early G dwarf and an early F dwarf will thus provide another good test of this scenario.

Additional theoretical work also remains. A comprehensive set of pre-main-sequence evolutionary tracks should be computed with varying core and envelope metallicities, and an emphasis on the mass of the outer convection zone with time. Heavy elements settle out of stellar photospheres if given enough time and these effects can also be included. Further refinements to the orbital migration problem should be done. Finally, the manner in which a giant planet spirals into a stellar photosphere should be studied in more detail.

We are pleased to thank P. Bodenheimer for useful discussions and a critical reading of the manuscript. We are grateful to G. Gonzalez for providing a prompt, insightful, and useful referee's report. This work was supported by a NSF Young Investigator Award, NASA Grant No. NAG 5-2869, and by funds from the Physics Department at the University of Michigan.

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Figure Captions

Fig. 1.— Enrichment trends for stars of mass $1.0M_\odot < M_* < 2.5M_\odot$. The reference case (*thick gray line*) shows the metallicity trend for a populations of stars with disk lifetimes t_D = 10 Myr, accretion index n=2, and 2 Jupiter masses accreted. The additional thin lines show the effect of varying each of these three parameters individually: The *short dashed lines* show trends expected from $N_{Jup} = 1, 3$. *Solid lines* show trends expected for disk lifetimes of 20, 15, 5 and 1 Myr. *Long dashed* lines show trends expected for $n = 1$ and 3.

Fig. 2.— Monte-Carlo simulation of metallicity enrichment due to accretion of planets. Metal enriched stars (obtained as described in the text) are shown as black dots. Arrows indicate the change in $T_{\rm eff}$ and Z resulting from metal enrichment. The solid black line shows a linear fit to the enhanced metallicity population, the dashed line shows a linear fit to the original distribution of metallicities and effective temperatures. Zero age F stars lying within a distance $d = 40$ pc of the Sun are shown as gray open circles (from the MS catalog). The solid gray line shows a linear fit to the metallicities of these stars. The minimum mixing

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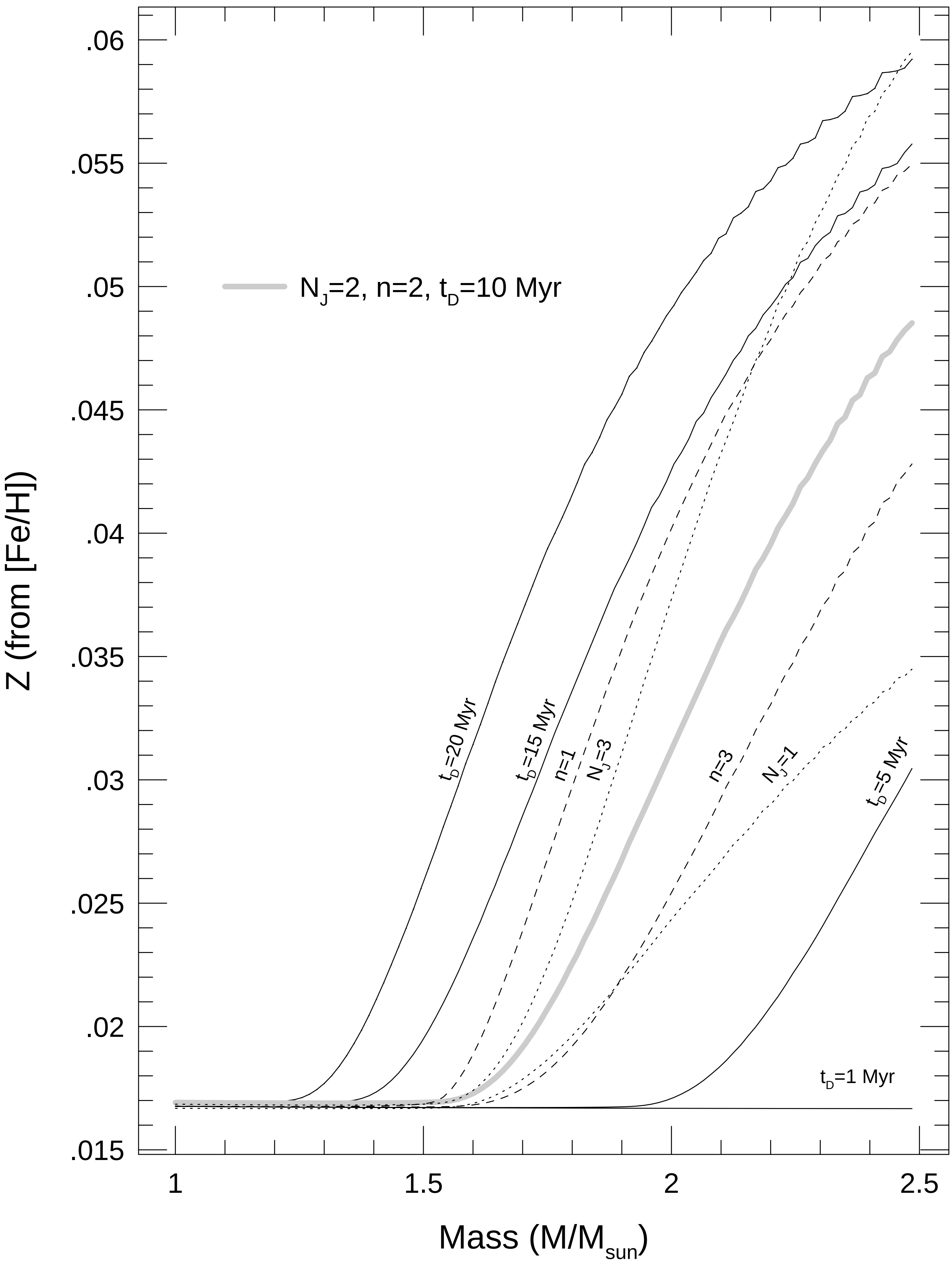
mass beneath the stellar photosphere is 4 M_{Jup}. The triangles indicate average metallicity values within 200K temperature bins.

Fig. 3.— Same as Figure 2 except that the minimum mixing mass beneath the stellar photosphere is 2 M_{Jup}.



N_J=2, n=2, t_D=10 Myr
t_D=20 Myr
t_D=15 Myr
n=1
N_J=3
n=3
N_J=1
t_D=5 Myr
t_D=1 Myr
Z (from [Fe/H])
Mass (M/M_sun)
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.055
.05
.045
.04
.035
.03
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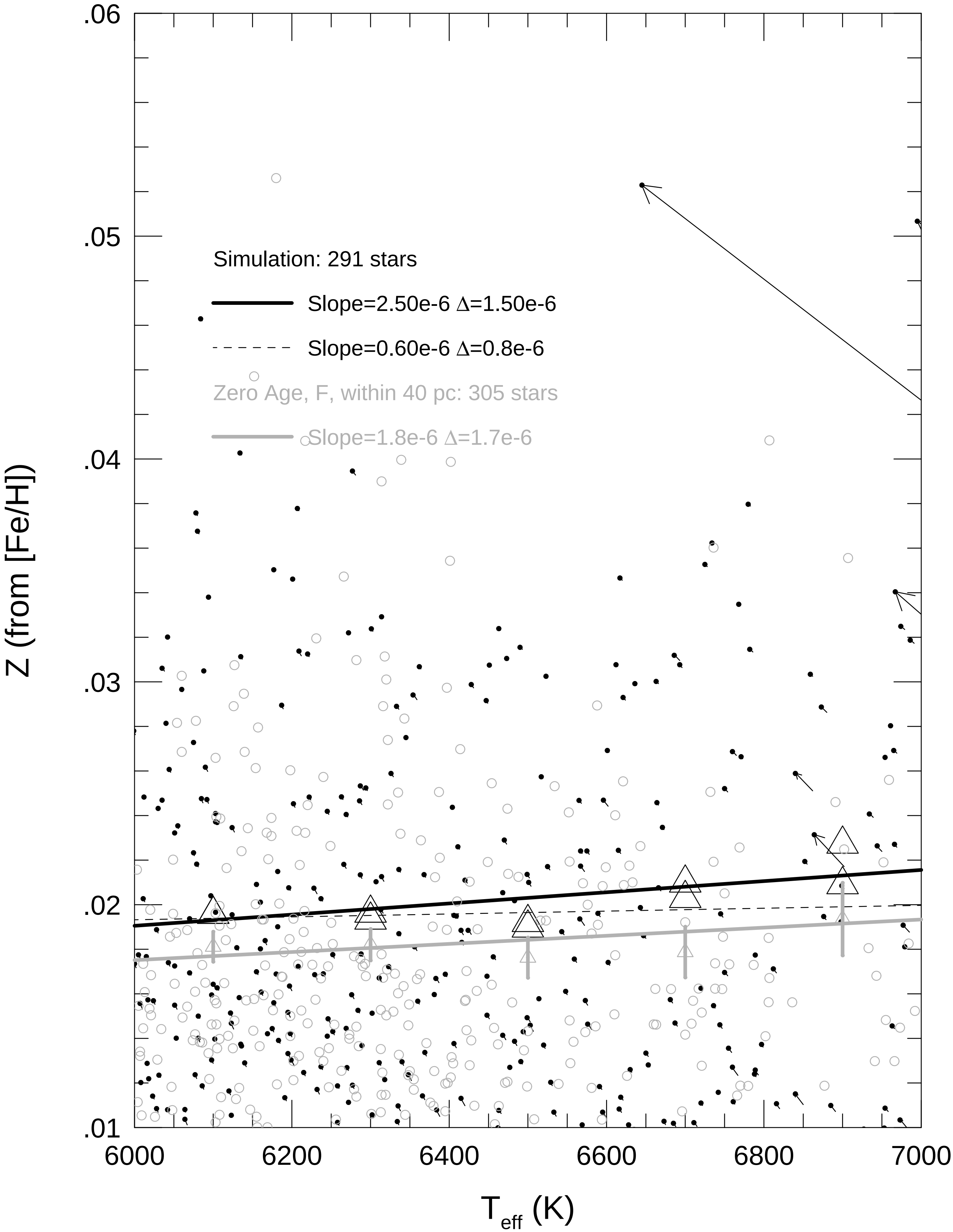
1
1.5
2
2.5



Simulation: 291 stars
Slope=2.50e-6 Δ=1.50e-6
Slope=0.60e-6 Δ=0.8e-6
Zero Age, F, within 40 pc: 305 stars
Slope=1.8e-6 Δ=1.7e-6
Z (from [Fe/H])
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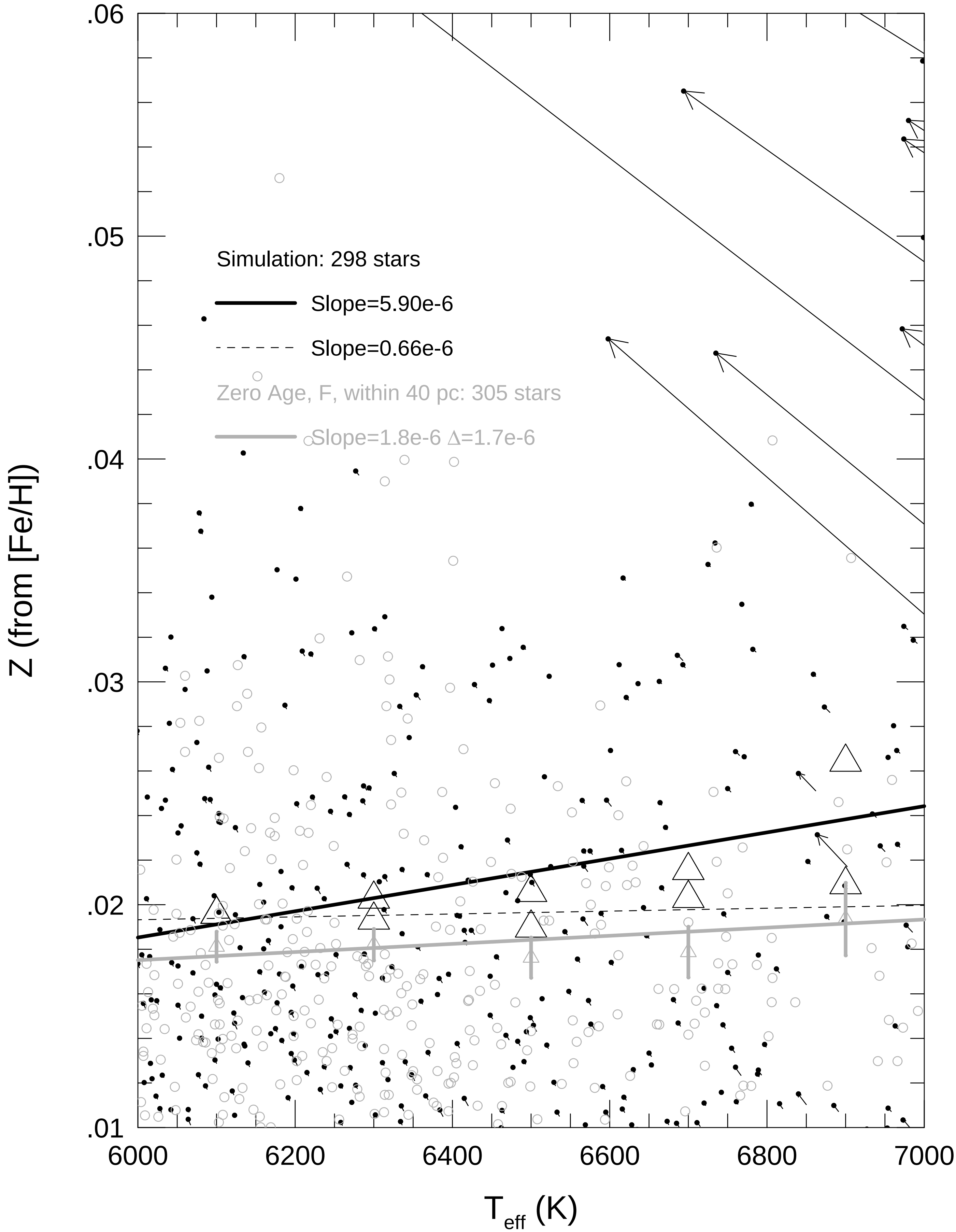
.05
.04
.03
.02
.01
6000
6200
6400
6600
6800
7000
T_eff (K)



Simulation: 298 stars
Slope=5.90e-6
Slope=0.66e-6
Zero Age, F, within 40 pc: 305 stars
Slope=1.8e-6 Δ=1.7e-6
Z (from [Fe/H])
.06
.05
.04
.03
.02
.01
6000
6200
6400
6600
6800
7000
T eff (K)